# A DOPPLER COMPENSATION SCHEME FOR RF COMMUNICATIONS USEABLE ON DYNAMICALLY RETARGETED PROJECTILES

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## 1. ABSTRACT

The use of dynamic retargeting to modify the impact point of an in-flight projectile is highly desirable for the Future Combat System (FCS). However, communications between the projectile and the ground is complicated by Doppler shift of the Radio Frequency (RF) carrier that is produced by the projectile's speed. Shifts from Ultra-High Frequency (UHF) frequencies can be as high as 7-8 kHz, which would overwhelm typical Frequency Shift Keying (FSK) changes of ±1 kHz. This paper proposes a Doppler compensation scheme to allow reliable RF communication between the ground and the projectile, when the projectile includes a Global Positioning System (GPS) receiver.

## 2. NOMENCLATURE

| | |
|---|---|
| c | Speed of light [$3*10^8$ m/sec] |
| $\Delta t$ | GPS refresh time |
| $\Delta f$ | Doppler frequency shift |
| $f$o | Transmitter carrier frequency |
| $\mathbf{R}_g$ | Position of the ground transceiver |
| $\mathbf{R}_{proj}(t)$ | Current projectile position |
| $\mathbf{R}_{proj}(t-\Delta t)$ | Previous projectile position |
| $\mathbf{R}(t)$ | Relative position between the projectile and the ground transceiver |
| $\mathbf{v}_{proj}(t)$ | Averaged projectile velocity |
| $\mathbf{v}_{rel}(t)$ | Relative velocity of the projectile and the ground transceiver |
| | **Discrete variables from GPS** |
| $\mathbf{a_E}$ | Unit vector in the Easting direction |
| $\mathbf{a_h}$ | Unit vector in the altitude direction |
| $\mathbf{a_N}$ | Unit vector in the Northing direction |
| $\mathbf{E}_x$ | Easting vector component |
| $\mathbf{h}_x$ | Altitude vector component |
| $\mathbf{N}_x$ | Northing vector component |
| $\mathbf{R}_x$ | Projectile position (discrete) |
| $\mathbf{v}_x$ | Projectile velocity (discrete) |
| | **Subscript Usage** |
| 1 | Previous time |
| 2 | Current time |
| g | ground communication position |
| 21 | Difference ($N_{21} = N_2 - N_1$) |
| 2g | Difference ($N_{2g} - N_2 - N_g$) |

## 3. INTRODUCTION

When two objects have relative motion with respect to each other, any RF communication will experience a Doppler shift as described below:

$$\frac{v_{rel}}{c} = \frac{\Delta f}{f_o} \tag{1}$$

For most RF applications, the relative speed is too small to significantly affect communications, however with gun-launched projectiles at speeds near 1000 m/s, this is not the case. Potential development of the ElectroMagnetic (EM) gun, with muzzle velocities potentially two to three times higher than this, will only make the projectile communication worse. Table 1 shows the Doppler shift using Inter-Range Instrument Group (IRIG) frequencies as examples.

**Table 1. Doppler shift for IRIG frequencies at various projectile velocities**

| $f_o$ | Howitzer 700 m/s | Tank 1000 m/s | EM gun 2000 m/s |
|---|---|---|---|
| 1485 MHz (L-band) | 3.47 kHz | 4.95 kHz | 9.90 kHz |
| 2245 MHz (S-band) | 5.24 kHz | 7.48 kHz | 14.97 kHz |
| 2350 MHz (Upper S-band) | 5.48 kHz | 7.83 kHz | 15.67 kHz |

These values give only an estimate of the frequency shift since a ballistic projectile's velocity is variable during the flight. Use of a rocket assist motor and course correction devices will lead to further variations of the Doppler shift during the flight, which cannot be predicted by the ground station.

The simplest solution to the Doppler problem is to just ignore it. The transceivers can be designed with a reception bandwidth large enough to receive the expected carrier frequency when the projectile is at its slowest and fastest velocity during its flight. This receiver however, will be more sensitive to noise and will take up large spectral bandwidth away from future designers. A second potential solution to is to minimize the Doppler by using a

| Report Documentation Page | *Form Approved*<br>*OMB No. 0704-0188* |
|---|---|



| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| **00 DEC 2004** | **N/A** | **-** |

| 4. TITLE AND SUBTITLE | 5a. CONTRACT NUMBER |
|---|---|
| **A Doppler Compensation Scheme For Rf Communications Useable On Dynamically Retargeted Projectiles** | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**U.S. Army TACOM-ARDEC Picatinny Arsenal, NJ 07806-5000** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR’S ACRONYM(S) |
| | 11. SPONSOR/MONITOR’S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT

**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES

**See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | |
| **unclassified** | **unclassified** | **unclassified** | **UU** | **6** | |

lower carrier frequency. However, this will require a larger transmitting and receiving antenna. While this will not likely be an issue with the ground station, it can be problematic for the projectile.

A third technique, proposed for satellite communications [Povey G. J. R., and Talvitie J., 1996], would require the projectile to broadcast a Continuous Wave (CW) signal on a null in the carrier band. The ground station then estimates the Doppler shift from this signal using a Fast Fourier Transform (FFT). This allows the ground station to raise its transmit frequency and to lower it reception frequency so that the projectile can receive and send on a designated center frequency as if there were no Doppler shift. However, this will require a larger battery on the projectile to provide the energy to transmit and might be used by the enemy as an indication of incoming fire.

A better solution is to make the Doppler frequency shift compensation on the projectile. This will be made possible by the addition of GPS receivers and Inertial Measurement Units (IMU) on many future projectiles. [Grace J., 2000, and Wells L. L., 2000]. The average velocity is calculated below using two successive GPS fixes and dividing by the GPS acquisition time.

$$\vec{\mathbf{v}}_{proj}(t) = \frac{\vec{\mathbf{R}}_{proj}(t) - \vec{\mathbf{R}}_{proj}(t - \Delta t)}{\Delta t} \tag{2}$$

The relative position between the projectile and the ground station is calculated as follows:

$$\vec{\mathbf{R}}(t) = \vec{\mathbf{R}}_{proj}(t) - \vec{\mathbf{R}}_{g} \tag{3}$$

The relative velocity between the projectile and the ground is determined by taking the component of the projectile's velocity in the direction of the **R**(t). This is accomplished by using the dot product as follows:

$$\left\|\vec{\mathbf{v}}_{rel}(t)\right\| = \frac{\vec{\mathbf{v}}_{proj}(t) \bullet \vec{\mathbf{R}}(t)}{\left\|\vec{\mathbf{R}}(t)\right\|} \tag{4}$$

Finally, the Doppler frequency shift can be determined. An example of this is plotted in Figure 1.

$$\Delta f = \frac{\left\|\vec{\mathbf{v}}_{rel}(t)\right\|}{c} f_o \tag{5}$$

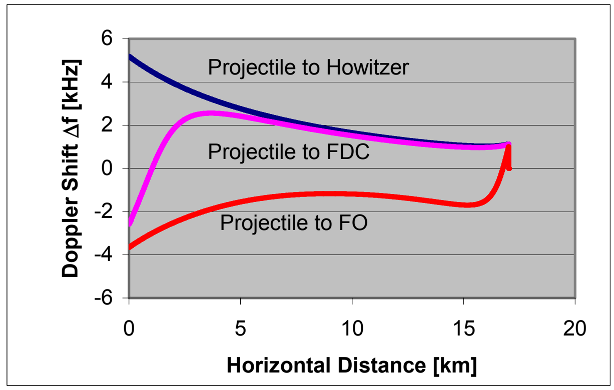


***Figure 1.*** *Calculated Doppler shift for a 2245 MHz carrier between a projectile and either the launching Howitzer, the FDC, or the FO. The projectile has a muzzle velocity of 693 m/sec, and is launched at a 45° angle.*

Just after the projectile is launched, the Doppler shift seen from the howitzer and Fire Direction Center (FDC) changes rapidly but the shift remains below 2 kHz for the second half of the flight. As the projectile nears the target, the difference in the Doppler shift between these two points becomes negligible. The Forward Observer (FO) however, observes a much more varied Doppler shift. Of specific note is the 3 kHz frequency change just prior to impact. This is the result of the projectile passing over the FO, and may limit communication from this location.

## 4. DOPPLER COMPENSATION SIMULATION

All the numerical simulations for this paper were performed in a Microsoft Excel spreadsheet. The projectile flight simulation was limited to ballistic flight. Calculations were performed using kinetics equations, modified by the addition of air friction, which was estimated to be proportional to the square of the projectile's velocity. The solution was numerically determined at ten millisecond intervals during the simulated flight. This interval was chosen to provide 100 data points between simulated GPS fixes.

U. S. Army doctrine includes three positions on the ground when controlling artillery projectiles: The FO, the FDC, and the firing howitzer. Any communication between the in-flight projectile and the ground will most likely be from one of these positions. Therefore, the simulation results in this paper are limited to these locations. They are arbitrarily assigned relative locations as seen in Figure 2.

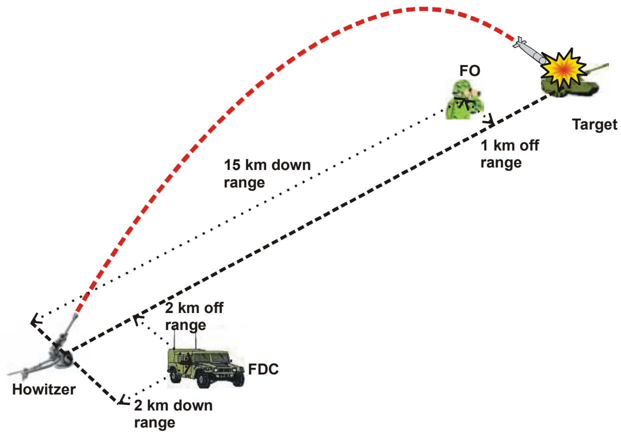


***Figure 2.*** *For this simulation the FDC is located 2 km downrange, and 2 km off axis. The FO is located 15 km downrange, and 1 km off axis. Range to the target is 17 km.*

### 4.1. The Doppler Compensation Processor

The processor that will be installed in the artillery projectile must be capable of a significant number of mathematical calculations. A slower processor will yield the solution too late to be effective, while a faster processor may require too much power, and, therefore, a larger battery. It would be desirable to use electronics already installed within the projectile as long as these computations do not impose a significant burden on the processor.

Currently the Precision Munitions Instrumentation Division, at Picatinny Arsenal, is working with the TMS320C2812 Digital Signal Processor (DSP), manufactured by Texas Instruments of Dallas, Texas. This DSP is being tested for applications to in-flight telemetry, it also appears to be a good candidate for the Doppler compensation testing.

The TMS320C2812 runs at 150 MHz and includes a low-cost 32-bit fixed-point Central Processing Unit (CPU) for Reduced Instruction Set Computing (RISC). For improved speed, the CPU includes six separate address/data buses, to allow reading programming instructions, along with reading and writing data in parallel. A compiler for C/C++ is available along with a native assembly language programming.

### 4.2. GPS to UTM Unit Conversion

Updated GPS location data will be provided to the projectile each second during the flight. This data is computed in the WGS84 (1984 World Geodetic System) units. The calculations to compute the distance traveled and required course corrections are simplified when done in a Cartesian coordinate system. Therefore, the WGS84 coordinates should be converted to the Universal Traverse Mercator (UTM) system.

Geographic Translator (GEOTRANS) software, written for the National Imagery and Mapping Agency by Northrop Grumman Information Technology Corp., performs a number of geographic coordinate conversions. The tranmerc function written in the C programming language of GEOTRANS version 2.2.3 was used for this paper. This function translates between the WGS84 and UTM coordinate systems. This program was used in the DSP timing simulation.

### 4.3. Discrete Doppler Calculations

After the update from the GPS system, and the conversion of those coordinates into the UTM system, the Doppler calculation can begin. Each position vector will be specified by a Northing, Easting, and altitude component. Unlike the analytic derivation in Section 3, this will have to be done with discrete values and is accomplished as follows:

$$\begin{aligned}\vec{\mathbf{R}}_1 &= N_1\vec{\mathbf{a}}_{\mathbf{N}} + E_1\vec{\mathbf{a}}_E + h_1\vec{\mathbf{a}}_{\mathbf{h}}\\ \vec{\mathbf{R}}_2 &= N_2\vec{\mathbf{a}}_{\mathbf{N}} + E_2\vec{\mathbf{a}}_E + h_2\vec{\mathbf{a}}_{\mathbf{h}}\\ \vec{\mathbf{R}}_{\mathbf{g}} &= N_g\vec{\mathbf{a}}_{\mathbf{N}} + E_g\vec{\mathbf{a}}_E + h_g\vec{\mathbf{a}}_{\mathbf{h}}\end{aligned} \tag{6}$$

The vector $\mathbf{R_1}$ defines the projectile's previous GPS position, $\mathbf{R_2}$ is the projectile's current GPS position, and $\mathbf{R_g}$ is the GPS position of the ground transceiver. During the flight, it is expected that the value of $\mathbf{R_g}$ will remain constant. Each position is expressed in terms of the unit vectors in the UTM coordinate system.

The projectile's relative velocity can be calculated by comparing the current position vector $\mathbf{R_2}$ to the former vector $\mathbf{R_1}$, along with the elapsed time Δt, which is nominally one second.

$$\begin{aligned}&\vec{\mathbf{v}}_{\mathbf{21}} = \frac{N_{21}}{\Delta t}\vec{\mathbf{a}}_{\mathbf{N}} + \frac{E_{21}}{\Delta t}\vec{\mathbf{a}}_{\mathbf{E}} + \frac{h_{21}}{\Delta t}\vec{\mathbf{a}}_{\mathbf{h}}\\ &\text{Where } N_{21} = N_2 - N_1,\ E_{21} = E_2 - E_1,\\ &\text{and } h_{21} = h_2 - h_1\end{aligned} \tag{7}$$

The position of the projectile relative to the ground is designated $\mathbf{R_{2g}}$, and calculated by the vector subtraction of the two position vectors $\mathbf{R_2}$ and $\mathbf{R_g}$.

$$\vec{\mathbf{R}}_{2g} = N_{2g}\vec{\mathbf{a}}_{\mathbf{N}} + E_{2g}\vec{\mathbf{a}}_{\mathbf{E}} + h_{2g}\vec{\mathbf{a}}_{\mathbf{h}}$$
$$\text{Where } N_{2g} = N_2 - N_g,\ E_{2g} = E_2 - E_g, \tag{8}$$
$$\text{and } h_{2g} = h_2 - h_g$$

Finally, the calculation of the relative velocity using the discrete location data is:

$$\left\|\vec{\mathbf{v}}_{\mathbf{rel}}\right\| = \frac{N_{21}\cdot N_{2g} + E_{21}\cdot E_{2g} + h_{21}\cdot h_{2g}}{\Delta t\sqrt{N_{2g}^2 + E_{2g}^2 + h_{2g}^2}} \tag{9}$$

The results of this expression should then be stored in memory such that the DSP can readily access the value. The Doppler compensation calculation from this point is done using equation (1) and can be quickly performed for each new transmission frequency if a spread spectrum frequency hopping modulation scheme is used.

### 4.4. Processor Time Delay

The GPS to UTM conversion and the Doppler compensation calculations were implemented with a computer program written in the C programming language. The computations required less than 8.3 milliseconds of processing time, using less than 1% of the CPU time available. Therefore, while the Doppler compensation computations are complicated, they can be accomplished on the projectile.

It should be pointed out that this simulation time did not include the time to acquire the GPS signal and transmit those results to the DSP. However, those times are expected to be short compared to the Doppler compensation calculation.

## 5. DISCRETE DOPPLER COMPENSATION EFFECTS

The GPS data is expected to be updated once a second for the duration of the projectile's flight. Therefore, the Doppler compensation calculation will also be updated once every second, but after a computational delay. If the projectile undergoes a radical change in velocity just after receiving a GPS update, the Doppler compensation will be in error until a new GPS location is received and the subsequent compensation value is calculated.

To model this error, the Doppler compensation of a simulated projectile was calculated at ten millisecond intervals. The DSP compensation was performed at one-second intervals and delayed for ten milliseconds to simulate the calculation time. These values were compared to the Doppler error, and plotted as a function of horizontal distance traveled in Figure 3.

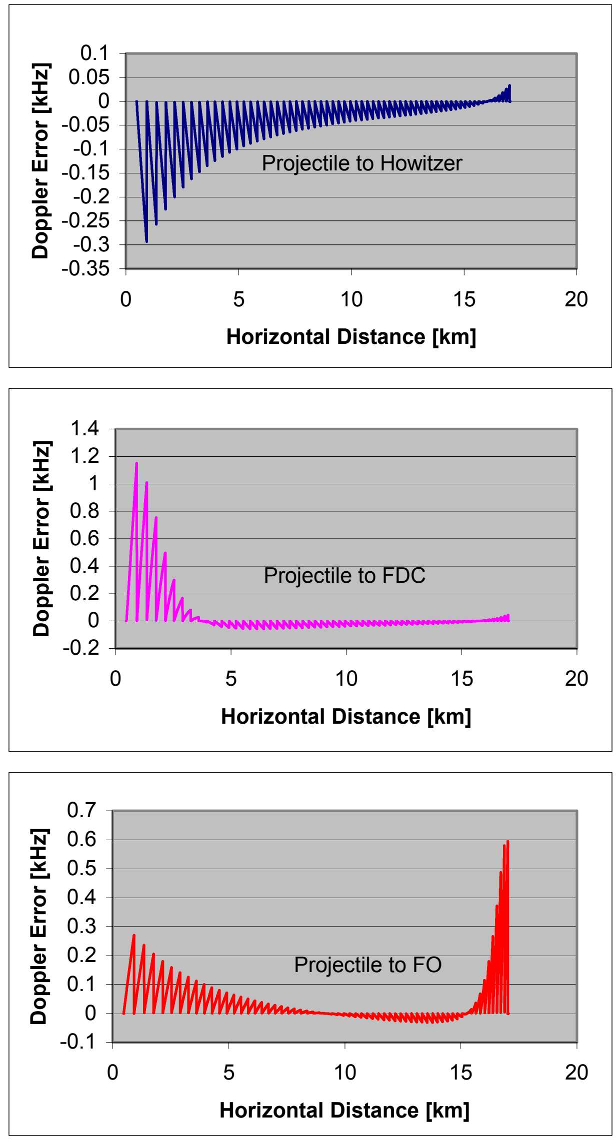


***Figure 3.*** *Calculated Doppler Error for a 2245 MHz carrier between a projectile and either the launching Howitzer, the FDC, or the FO. The error is reset every second with each GPS location update. The maximum error is observed when the relative velocity is changing quickly. For the Howitzer and the FDC, this occurs close to launch, but for the FO this occurs just after launch, but more severely near the impact point.*

The Doppler compensation shows small errors when the relative motion of the projectile is changing slowly. For the firing platform, the relative velocity's rate of change is highest just after launch but this drops rapidly as the projectile gets closer to the target.

## 6. DOPPLER COMPENSATION OPTIONS

The prime motivation for a projectile communication system is the ability to retarget an in-flight projectile. The only individual that should exercise this option is the Maneuver Commander through his designated representative, the FO. This limitation is consistent with the U. S. Army's chain of command and maintains the original ownership of the round.

### 6.1. Compensation for the FDC Location

In the traditional artillery command structure, the FO requests fire from the battery. The FDC computes the firing solution and transmits the order to the firing battery. The FO provided only rudimentary firing information because of the limited computing resources available. Using this model, the FDC would be the best location for Doppler compensation since it would be the only location with the computational ability to provide updated targeting.

The on-board Doppler compensation scheme will work well for the FDC location since the majority of the errors take place just after launch. This is normally a period when the projectile is involved with functions such as: deploying control surfaces, roll cessation, powered flight, and GPS signal acquisition, where communications are not essential. Course corrections, along with the required communications, would be delayed until after this period and closer to time when the projectile is near the flight apex.

### 6.2. Compensation for the FO Location

However, the disadvantage of this arrangement is that the FO, who will be first to know of the need for retargeting, will have to format and transmit the request to the FDC for action. This time delay could be eliminated if the FO is equipped with sufficient computing power and a transmitter capable of ground to projectile communications.

The discrete Doppler compensation, from the FO's location, is not as well behaved as it is from the FDC. Just prior to impact with the target, the rapidly changing relative velocity causes the Doppler compensation to be erroneous. While this behavior is only seen in the last ten seconds of the projectile's simulated flight, in general, these errors will start near the time the projectile passes over the FO position and last until target impact. Depending upon the terminal guidance in the projectile, this could potentially be the most critical time for communicating an updated solution.

### 6.3. Additional Corrections From the IMU

Increasing the frequency of the projectile's location data, provided by the GPS, can reduce the Doppler error observed by the FO. Alternately, the IMU can provide this data between GPS fixes. All systems that use GPS navigation should include a backup IMU in the event of jamming or loss of GPS satellites. Therefore, this information should already be available.

Figure 4 shows the Doppler error at the FO position when the compensation has been modified by including four fixes per second, one by GPS and three by IMU. The maximum error observed by the FO, just prior to impact with one position fix per second, is 600 Hz. When the Doppler compensation is performed four times per second, the maximum error is reduced to approximately 150 Hz. Therefore, the improvement in the Doppler compensation is linearly proportional to the frequency of position data available. However, this improvement comes with the price of increasing the CPU loading to perform the Doppler compensation calculations more often.

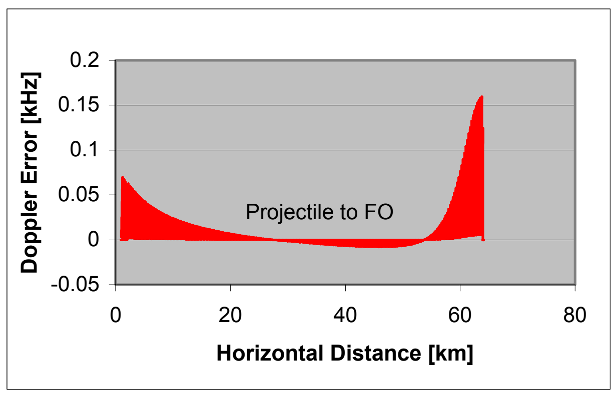


**Figure 4.** *Calculated Doppler Error for a 2245 MHz carrier between a projectile and the FO. The error is reset every second with each GPS location update and on every quarter second by the IMU location. The peak error is observed from the FO just prior to impact has been reduced to 150 Hz.*

## 7. CONCLUSIONS

Adding dynamic retargeting functionality to a projectile will require a communications system between the projectile and the ground. Provided that the projectile's navigational system includes a GPS receiver, the Doppler shift from relative motion can be significantly cancelled using onboard components. Real time calculations will impose only a very small burden on the limited computer processing available. Additional data

from the IMU can be used to further improve the accuracy of these calculations.


## ACKNOWLEDGEMENTS

The author wishes to express thanks to Philip R. Wetzel of High Performance Technologies, Inc. and Stewart Van Weele of Management Technology Associates, Inc. for their assistance with the software coding and DSP simulation.


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